INDIRECT PLANET DETECTION WITH GROUND-BASED LONG-BASELINE INTERFEROMETRY

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Abstract.

Narrow-angle astrometry with long-baseline infrared interferometers can provide extremely high accuracies as required for indirect planet detection. Narrow-angle astrometric interferometry exploits the properties of atmospheric turbulence over fields smaller than the interferometer baseline divided by the atmospheric scale height. For such fields, accuracy is linear with star separation, and nearly inversely proportional to baseline length. To exploit these properties, the interferometer observes a relatively bright (<13 mag_K) target in the near infrared at 2.2 μm, and uses phase referencing to find a reference star within the 2.2 μm isoplanatic patch. With this technique faint references can be found for most targets. With baselines >100 m, which also minimize photon-noise errors, and with careful control of systematic errors by using laser metrology, accuracies of tens of microarcseconds/$\sqrt{\text{hour}}$ should be possible.

Key words: planet detection -long-baseline interferometry –astrometry -atmospheric effects - techniques: interferometric

1. Introduction

Indirect detection of exoplanets senses the presence of a planet around another star by observing the motion of the star about the system barycenter. These planetary signaturea are generally quite small. A Jupiter-Sun system observed from 10 pc would exhibit a peak-to-peak signature of 1 mas with a 12-yr period. The signature

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is clearly smaller for a less massive planet, a more massive star, or a faster orbital period. Narrow-angle astrometry on the ground using astrometric telescopes with modern detectors exhibits accuracies of the order of 2-3 milliarcseconds in one night (Monet & Dahn 1983, Gatewood 1987), limited by the atmosphere, which is inadequate for any comprehensive planet search. However, the accuracy of these current techniques is far from the ultimate accuracy that can be achieved when observing through atmospheric turbulence.

The key to obtaining high astrometric accuracies is a detailed understanding of the error sources in the measurement-fundamentally, for ground-based measurements, atmospheric turbulence-and the design of a measurement technique to control the error or to exploit the particular characteristics of the error. One technique which can reach the ultimate accuracies allowed by the atmosphere is long-baseline interferometry. The key features of long-baseline interferometry in this application are dual-beam operation to perform a simultaneous differential measurement between a target and reference star, long baselines ($\geq$ 100 m) to reduce atmospheric and photon-noise errors, infrared observations with phase referencing to increase sensitivity in order to locate nearby reference stars, and laser metrology to control systematic errors. The atmospheric limit for an optimized system can reach 10 $\mu as/\sqrt{hr}$, with photon noise and systematic errors controlled to a similar level. A system with performance close to these limits could conduct a comprehensive search for Jupiter-mass planets around stara of various spectral types, and for short-period Uranus-mass planets around nearby M and K stars.

2. Atmospheric Limitations

The detailed expression for the atmospheric error in a differential astrometric measurement follows from a straightforward derivation using conventional models of atmospheric turbulence (Lindegren 1980, Shao & Colavita 1992). The key parameters in the model are the baseline length (or telescope diameter) B, and the separation vector θh, where θ is the angle between the two stars and h is the atmospheric height, ~5–10 km. In an ordinary differential astrometric measurement, the separation θh is much larger than the telescope diameter. In this case the astrometric error is only weakly dependent on the star separation (as $\theta^{1/3}$), and not dependent on the baseline length; this dependence has been confirmed by measurements with the Multichannel Astrometric Photometer (Han 1989).

However, when θh is smaller than the baseline length, the error behavior changes significantly.[1] In this case the error variance, σ_δ^2, of a t-second differential measurement is given by

$$\sigma_\delta^2 \simeq 5.25\, B^{-4/3}\theta^2 \int dh\; C_n^2(h)\, h^2 V^{-1}(h) t^{-1}\,, \qquad \theta < B/h,\ \ t \gg B/V, \tag{1}$$

where $C_n^2(h)$ and $V(h)$ are the turbulence and wind-speed profiles. With the substitution of atmospheric parameters appropriate to an excellent site like Mauna Kea, this expression yields (Shao & Colavita 1992)

$$\sigma_\delta \simeq 300 B^{-2/3} \theta t^{-1/2} \text{ arcsec}, \qquad \theta \ll B/3000,\ \ t >> B/10, \tag{2}$$

with B in meters and θ in radians. The key features in this very-narrow-angle regime are the linear dependence of the error on star separation, and the nearly linear

[1] The breakpoint between regimes, $\theta = B/h$, is sometimes referred to as the isokinetic angle.

Fig. 1. Narrow-and very-narrow-angle astrometric error for several baseline lengths using measured Mauna Kea turbulence profiles and an integration time of 1 hr.

decrease in error with increasing baseline length. Figure 1 plots the complete error behavior for several different baseline lengths to show more clearly the dependencies of the *error. From* the graph or from the expressions above, it is clear that with long baselines and small star separations, very small astrometric errors can be achieved, e.g., with a 200 m baseline and a 15” star separation, the atmospheric error is 10 $\mu as/\sqrt{hr}$.

There are fewer confirming measurements in this very-narrow-angle regime than in the more conventional narrow-angle regime. However, recent star-trail measurements at Mauna Kea (Gatewood 1991) show a marked break from $\theta^{1/3}$ behavior at small separations. In addition, recent measurements of wide (*3”) binaries with the Mark III stellar interferometer on Mt. Wilson, modified to simultaneously detect the fringe packets from the primary and secondary, have yielded preliminary results which are consistent with the expressions above.

There are some additional points about the error behavior which should be emphasized. 1) As is clear from the $t^{-1/2}$ dependence in the expression above, the error is white for long integration times; this is unlike the behavior of an absolute astrometric measurement. 2) The derivation above does not depend upon perfect frozen flow between apertures, and is based on the most conservative orientation of the baseline and star-separation vectors. In addition, this derivation uses a conservative (infinite outer scale) Kolmogorov model. 3) The result above is essentially identical for telescopes and interferometers. While it is clear that, unlike an interferometer, a telescope acts as a spatial filter for spatial scales smaller than the telescope diameter, a detailed examination of the integral leading to Eq. 1 shows that most of the residual error for long integration times $(t >> B/V)$ is attributable to large spatial scales, rather than to those filtered by the telescope. Thus, there is no significant difference in the astrometric performance between interferometers and telescopes of the same size, although in practice, the long baselines necessary to exploit the characteristics of the atmospheric error are moat easily achieved with an interferometer. It is also worth recalling that the position of the centroid of a star's position as measured with a telescope depends. only on a contour integral around the periphery of the telescope (Hogge and Butts 1976); i.e., the interior phase distribution doesn 't matter: an annular telescope has precisely the same statistics of centroid motion as a filled aperture of the same diameter. Thus, this fact emphasize that it is the long baselines of the telescope's u-v coverage that are important to its astrometric performance.

3. Implementation

To exploit the atmospheric limits given above requires the reduction of photon noise and systematic errors to similar levels. Interferometers offer significant advantages over conventional telescopes in reducing these errors. For the case of photon noise, the contribution to astrometric error is proportional to $(\lambda/B)/\mathrm{SNR}$, i.e., to the diffraction-limit of the interferometer over the photometric signal-to-noise ratio, so that long baselines reduce the photon-noise error (as B^{-1}) along with the atmospheric error (as $B^{-2/3}$ in the very-narrow-angle regime). In addition, compared with a telescope, an interferometer has an easily monitored geometry in order to control systematic errors.

The instrument configuration considered in this section is a long-baseline interferometer operating at 2.2 pm. The aperture diameter is chosen as ~ 1.5 m, which is readily phased for operation at that wavelength with simple tip-tilt correction. There are several reasons for choosing the 2.2 μm band. One is that for typical cool stars, say K5, the fringe-tracking limiting magnitude of a 2.2 μm interferometer with large apertures is several magnitudes greater than that of a visible-wavelength interferometer. A second reason is that the isoplanatic patch at 2.2 μm is much larger than at visible wavelengths: $\sim$15–20" rather than $\sim$3–4". While the isoplanatic angle is quite different from the isokinetic angle discussed above, it does play a role in achieving high astrometric accuracies. This is because the magnitude of a reference star which yields a photon-noise error consistent with the desired atmospheric error is significantly fainter than the fringe-tracking limiting magnitude of the interferometer. Thus, to use faint reference stars nearby the target star in order to minimize the atmospheric error, a means of increasing the coherent integration time is needed. The technique used is phase-referencing, whereby the fringe position of the target star is used to stabilize the fringe position of the reference star, allowing coherent integration times well in excess of those allowed by atmospheric turbulence. However, like adaptive optics, this technique is only applicable within the isoplanatic patch, and thus the large 2.2 μm isoplanatic patch offers significant advantages in finding reference stars.

A detailed numerical example is worked in Shao & Colavita (1992); in summary, a 200-m baseline interferometer using 1.5-m telescopes was assumed. For a 15” separation between the target and reference stars, the atmospheric limit is 10 $\mu as/\sqrt{hr}$. The photon noise from the target star, assumed brighter than 13 mag_K, is negligible compared to the atmospheric noise. Using the target star to phase-reference within the isoplanatic patch, the reference star can be as faint aa 17.5 mag_K and still achieve a photon-noise error no larger than 10 $\mu as/\sqrt{hr}$. Assuming average star distributions, scaled according to spectral type, it can be shown that reference stars of this magnitude should be available within the isoplanatic patch over moat of the sky.

4. Implementation Details and Future Instruments

To achieve the performance described above requires care in implementation, but does not require, instrumental components beyond the current state of the art. The key features of an instrument which can demonstrate high-accuracy narrow-angle astrometry are phase-coherent fringe tracking at 2,2 μm with high sensitivity and a dual-star feed system. The latter device sends two beams from each interferometer aperture though separate delay lines to separate two-way beam combiners. A corner-cube retroreflector is mounted directly in front of (or on the surface of) the siderostat mirror, and its position is monitored using laser metrology from each beam combiner to control systematic errors to the required precision. The relative accuracy that must be achieved is ~10 nm, which is well within the capabilities of laser metrology systems. However, because of the narrow fields involved, many errors sources are common mode. For example, the absolute baseline vector need only be known to ~100 pm—a factor of 100 leas accurate than what has been achieved in wide-angle astrometry with the Mark 111 stellar interferometer (Shao et al. 1988, Shao et al. 1990).

In order to develop the technology for narrow-angle interferometric astrometry, as well as to validate the underlying atmospheric theory, NASA has recently funded, as part of the TOPS (Toward Other Planetary Systems) program (TOPS Report 1992), the TOPS-O Testbed Interferometer. This interferometer is being specifically y optimized for narrow-angle astrometry, using a dual-star feed, laser metrology, and high-sensitivity phase-coherent fringe tracking using array detectors at 2.2 pm. The instrument will use modest collecting apertures, ~40 cm clear aperture, and will nominally be installed at Palomar Mountain. Compared to a more optimized instrument, the major compromise in this low-cost prototype is the aperture diameter, which will limit sensitivity and hence the fraction of the sky over which very nearby reference stars can be found. However, the instrument will demonstrate the necessary technology and validate the atmospheric models to the limit set by the site. It will also be able to begin a modest observational program.

As a testbed, technology development is the primary goal of the Palomar interferometer: the lessons learned and the technology developed will transfer directly to the proposed Keck Interferometric Array (KIA)(Meinel et al. 1992, TOPS Report 1992). The KIA would combine the two Keck 10-m telescopes with four movable 1,5-m outrigger telescopes to form a powerful array for synthesis imaging as well aa for astrometry. In its astrometric mode, the array would use the four outrigger telescopes in an orthogonal array with baselines of* 120 m. With the excellent seeing at the site, plus the sensitivity allowed by the large aperturea in order to select nearby reference stars, the outrigger array should be able to achieve astrometric accuracies of leas than 30 $\mu as/\sqrt{hr}$; better performance is possible by incorporating one or both 10-m telescopes.

5. Conclusion

Over small fields the atmospheric limits for narrow-angle astrometry are surprising small. However, to achieve the ultimate limits set by the atmosphere requires the long baselines which can only be achieved with an interferometer. An interferometer with a 200 m baseline at a good site can measure the angle between two stars 15” apart to 10 $\mu as/\sqrt{hr}$. To achieve the sensitivity to find suitable references nearby an arbitrary target requires the use of modest ($\sim$ 1.5 m) apertures and phase referencing at 2.2 μm to increase the coherence time within the isoplanatic patch. To control errors to the appropriate level requires a dual-star feed with appropriate laser metrology. The recently funded TOPS-O Testbed Interferometer will demonstrate the technology for narrow-angle interferometric astrometry, and begin a modest detection program for selected targets. The technology and techniques would then be transferred to the proposed Keck Interferometric Array, which should be able to achieve astrometric errors of less than 30 $\mu as/\sqrt{hr}$. This instrument could conduct a comprehensive planetary-search program for Jupiter- and Saturn-mass planets around nearby stars of spectral types M-F, and for Uranus-mass planets in 10-yr orbits around nearby M and K stars.

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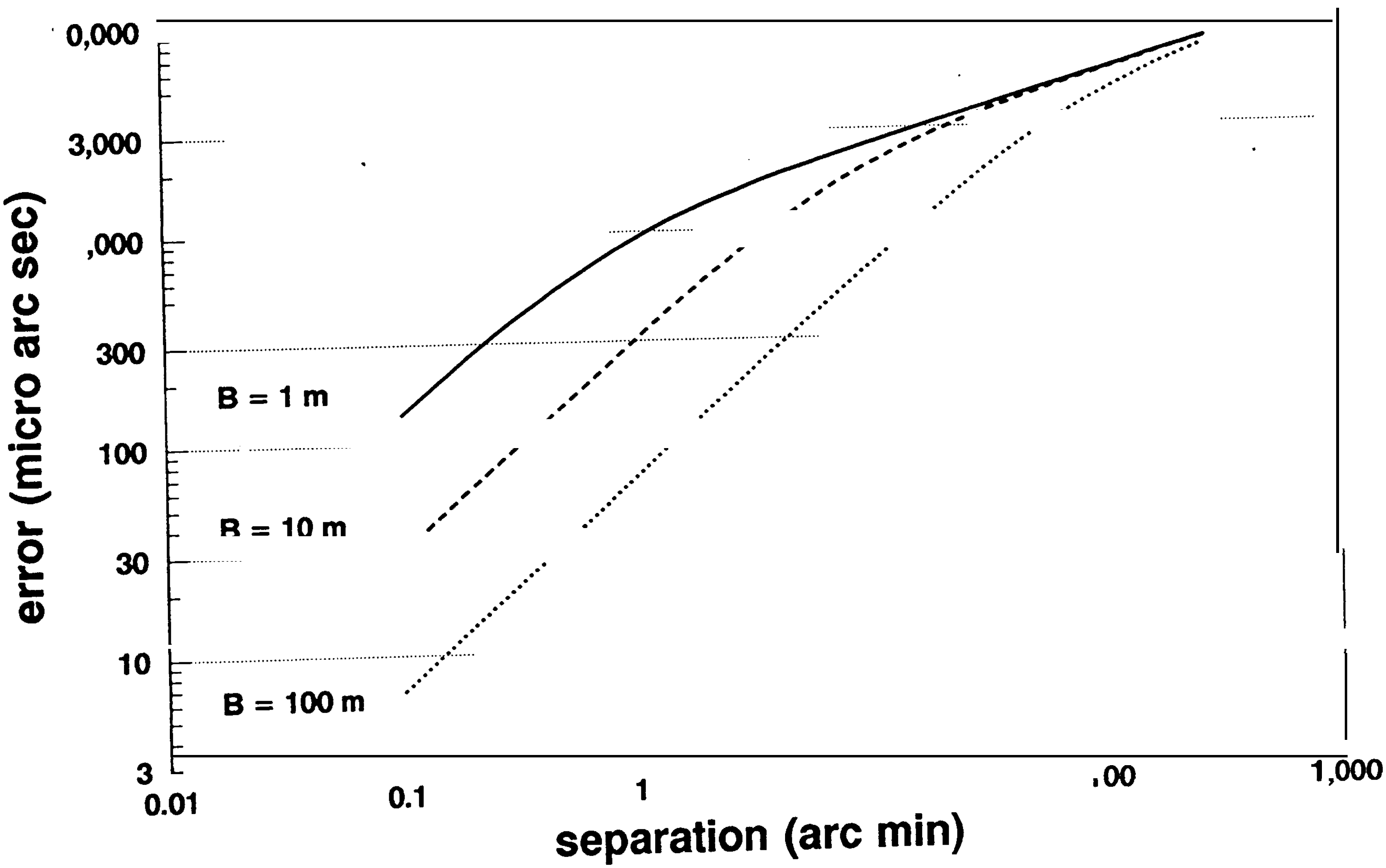

0,000
3,000
,000
300
100
30
10
3
B = 1 m
B = 10 m
B = 100 m
0.01
0.1
1
,00
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error (micro arc sec)
separation (arc min)